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ON THE RELATION BETWEEN THE GENERATION OF A LIFT FORCE ON A WING AND THE CHARACTER OF THE FLOW IN THE BOUNDARY LAYER*

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Classical wing theory, as is known, is based on a model of an ideal fluid devoid of any viscosity. Such simplification permits obtaining far-reaching conclusions of great practical value. At the same time the simplified representation of the actual medium as an ideal fluid does not permit explaining certain essential phenomena, such as for example the arising of the circulation and lift force at the start of the wing motion.

In the present article, containing fundamental results of an investigation conducted by the authors at MAI, an explanation is given of the formation of the vortex system of the wing, corresponding to steady motion, and experimental data presented that confirm this explanation.

We consider a straight wing of sufficiently large span so that the flow may be considered as two-dimensional. The flow regime in the boundary layer we shall consider as laminar.

Along the direction of flow there is, first of all, encountered a considerable velocity gradient of the potential flow near the leading edge of the wing. Since the intensity of manifestation of the viscosity of the medium is connected with the velocity gradient, the part played by the viscous medium in this region should be considerable. As a consequence of the effect of the viscosity, vortices arise here with axes parallel to the leading edge; they travel within the boundary layer along the surface of the wing, gradually covering its entire surface.

As will be shown, the vortices traveling along the lower surface of

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the wing reach the rear stagnation points (trailing edge) earlier than the vortices traveling along the upper surface. As a result, at the instant when the vortices moving along the upper surface reach the trailing edge a certain number of vortices shed from the lower surface of the wing appear in the free flow. These vortices, because of the unsteadiness of the thin vortex sheet, roll up into a discrete vortex, which represents the starting vortex. In the following instants of time, vortices of approximately equal circulation are simultaneously shed from the upper and lower wing surfaces so that their total circulation in the free flow is equal to zero. At each instant a
greater number of vortices are situated on the upper surface of the wing F
(at an angle of attack greater than zero) than on the lower surface and they 2
have a certain excess circulation which in steady motion represents the 6
circulation about the wing.

Contrary to the explanation sometimes given [1, 2] of the cause of the origin of the starting vortex, the latter is not connected with the fact that the trailing edge of the wing is sharpened. In Fig. 1 and 2 are shown photographs of the starting and stopping vortices obtained at the MAI laboratory in the case of a wing of the usual profile and a profile in the form of an elliptical cylinder. In both cases the phenomena are very similar.

Fig. 1. Starting and stopping vortices in the case of a wing of the usual profile for $\alpha > 0$.

In order to establish what vortices the starting and stopping vortices consist of, the upper and lower surfaces of the wing were covered with a paint of different color: the lower one black and the upper one white. On all photographs it was clearly seen that the color of the liquid was different: the starting vortex is essentially dark in color while the stopping vortex is white. This means, in correspondence

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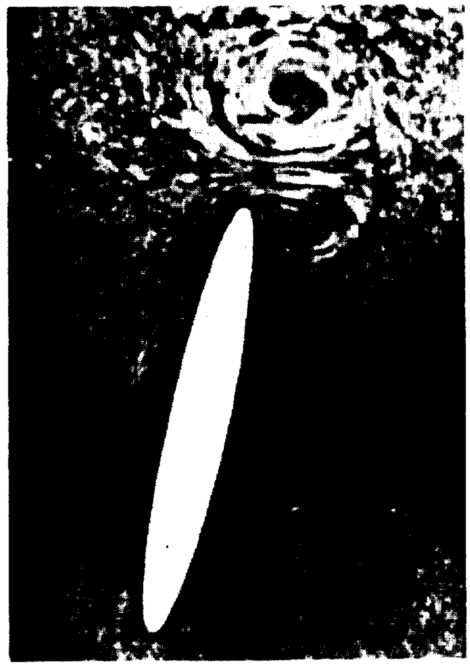

Fig. 2. Starting and stopping vortices in the case of an elliptical cylinder for $\alpha > 0$.

with the explanation given above, that the first is formed from the vortices of the lower surface of the wing while the second is formed from the vortices of the upper surface.

In order to estimate the magnitude of the velocity of displacement of the vortices formed at the leading edge of the wing along its surface let us consider the special case of the sudden start up of the motion of a flat plate at zero angle of attack.

In this special case the velocity of motion of the vortices along the upper and lower surfaces is the same; both groups of vortices simultaneously reach the trailing edge of the plate so that the circulation in the steady motion is equal to zero.

In accordance with the considerations adduced above, the flow picture in the boundary layer of the sections of the plate should be different depending on whether or not the vortices formed at the leading edge of the plate have reached this section. The flow in the boundary layer thus bears an unsteady character whereas the velocity of the potential flow for sufficiently large initial acceleration may be considered independent of the time. The same problem was considered by G. Blasius [3] and later by S. Goldstein [4]. For the velocity components parallel and normal to the surface Blasius obtained expressions in the form of the series:

$$\bar{u} = \frac{u}{V} = \zeta_0'(\eta) + V' t\zeta_1'(\eta) + t^2[VV''f(\eta) + V'^2\zeta_2'(\eta)] + \dots,$$
$$\bar{v} = \frac{v}{V} = -\frac{2\sqrt{\nu t}}{V}\{V'\zeta_0(\eta) + t(V'^2 + VV'')\zeta_1(\eta) + \dots\}, \tag{1}$$

where V, V', V''... are the velocity of the potential flow and its derivatives; the nondimensional coordinate η is connected with the real coordinate y by the relation:

$$\eta = \frac{y}{2\sqrt{\nu t}}. \tag{2}$$

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The functions $\zeta_0(\eta)$, $\zeta_1(\eta)$ ... are given by the expressions:

$$\zeta_0'(\eta) = \frac{2}{\sqrt{\pi}}\int_0^{\eta} e^{-\eta^2}\, d\eta,$$
$$\zeta_1'(\eta) = \frac{6}{\pi}\eta e^{-\eta^2}\int_\infty^{\eta} e^{-\eta^2} d\eta + \frac{2}{\pi}(2\eta^2 - 1)\Big[\int_\infty^{\eta} e^{-\eta^2} d\eta\Big]^2 + \frac{2}{\pi}e^{-2\eta^2} +$$
$$+ \frac{1}{\sqrt{\pi}}\eta e^{-\eta^2} - \frac{4}{\sqrt{\pi}}\int_\infty^{\eta} e^{-\eta^2} d\eta - \frac{4}{3\pi}e^{-\eta^2} +$$
$$+ \Big(\frac{3}{\sqrt{\pi}} + \frac{4}{3\pi^{3/2}}\Big)\Big[\eta e^{-\eta^2} + (2\eta^2 - 1)\int_\infty^{\eta} e^{-\eta^2} d\eta\Big]. \tag{3}$$

For the special case considered, the derivatives V', V'', ... are different from zero only in the immediate neighborhood of the leading edge of the plate. We shall assume that this edge has a sufficiently smooth form, so that over the entire extent the pressure gradient in the external flow has no positive values and reduces to zero at a certain distance from the edge.

If in expressions (1) we restrict ourselves to three terms of the series, then in that part of the plate where the velocity of the potential flow increases from zero to its full value (the region of the leading edge), we obtain for the velocity component parallel to the surface of the plate the following expression:

$$\bar{u} = \zeta_0'(\eta) + V' t\zeta_1'(\eta) + t^2[VV''f(\eta) + V'^2\zeta_2'(\eta)], \tag{4}$$

while in that part where the velocity of the potential flow is constant:

$$\bar{u} = \zeta_0'(\eta). \tag{5}$$

In this latter region of flow, the velocities in the boundary layer at a given distance from the plane of the plate continuously decrease with time approaching zero as t approaches infinity, since for $\eta \to 0$ we have $\zeta_0' \to 0$.

The thickness of the boundary layer in this region of flow, determined from the usual condition $u_\delta = 0.99V$, is equal to

$$\delta \cong 4\sqrt{\nu t}. \tag{6}$$

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The above given relations for the second region of flow hold true up to the instant when the vortices moving from the leading edge reach the plate section under consideration. At this instant, the flow regime in the boundary layer changes over and the expressions (5) and (6) lose their applicability. It is necessary to define this instant of time.

To simplify the computations we shall assume that the velocity distribution in the potential flow has the form represented in Fig. 3. With a schematization of this kind, vortices are formed simultaneously in the entire region ($0 \leq x \leq x_a$). In this case we have therefore two clearly separate regions: the region in which the vortices are generated and the region within which the vortices travel.

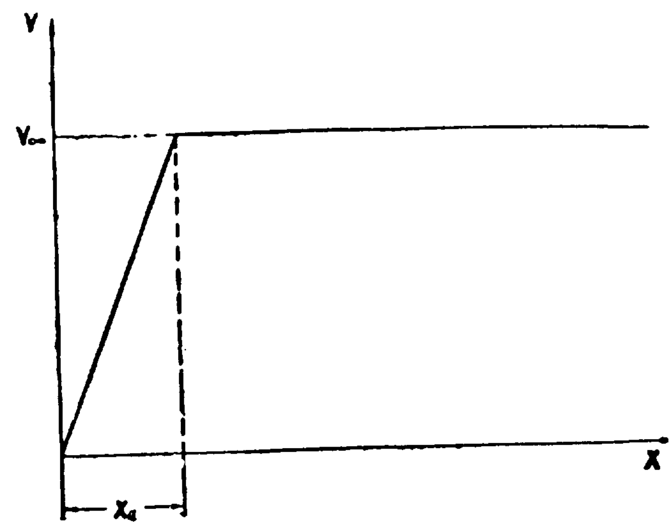

Fig. 3. Schematic velocity distribution in the potential flow about a plate.

With regard to the transition of the unsteady Blasius flow to the steady flow, the following may be said. The dissipation for a steady flow in the boundary layer with given external conditions is a constant magnitude;

where k is a magnitude of the order of smallness of h/b.

The value of the integral entering into expression (16) is greater than the value of the integral in (17); this means that in this case, too, the vortices moving over the lower surface overtake the vortices of the upper surface.

After the vortices moving over the lower surface reach the stagnation point of the flow, coinciding at that instant with the stagnation point of the irrotational flow, the picture of the flow about the wing changes. The vortices of the lower surface are shed from the wing while the vortices of the upper surface have not yet reached the stagnation point. As a result a circulation arises about the wing, as was pointed out at the beginning of this paper.

With the object of experimentally checking the above conclusions, based on certain assumptions and therefore bearing an approximate character, tests were conducted at the MAI laboratory whose general features are described below.

In a trough filled with water, a flat plate set at zero angle of attack was imparted a motion with the aid of an electric motor. Over the entire length of the trough, thin streamlets of a colored liquid were initially introduced whose density and viscosity did not differ from the corresponding values of the water. In the process of the motion the streamlets were deformed, which permitted determining the thickness of the boundary layer at different cross-sections of the plate at different instants of time. The shape of the streams was fixed by a moving picture camera with a speed of 12 to 32 frames per second. In Fig. 5 is shown a specimen of a frame obtained in this experiment. The Reynolds number with respect to the chord of the plate lay between the limits of $7 \cdot 10^4$ to $30 \cdot 10^4$, which assured a laminar boundary layer over its entire length. With the object of obtaining a different viscosity of the medium, the temperature of the water varied during the tests.

The results of the test were reduced to the two parameters:

$$\begin{aligned} \sqrt{\bar{x}} &= \sqrt{\frac{x}{x - x_0}}, \\ \bar{y} &= \frac{y}{2.77\sqrt{\nu t}}, \end{aligned} \qquad (18)$$

where x is the coordinate of a stream filament relative to the plate at the instant of time t, x_0 is the same for the initial instant, ν is the kinematic viscosity coefficient.

It can be shown that between these two parameters there should theoretically exist a linear dependence in the case of steady flow in the boundary layer. The abscissa bounding, on the graph of experimental values, the region of linear dependence of $\bar{y}$ on $\sqrt{\bar{x}}$ permits determining the velocity of propagation of the effect of the leading edge on the character of motion in the boundary layer.

The results of the evaluation of the experimental data obtained by the

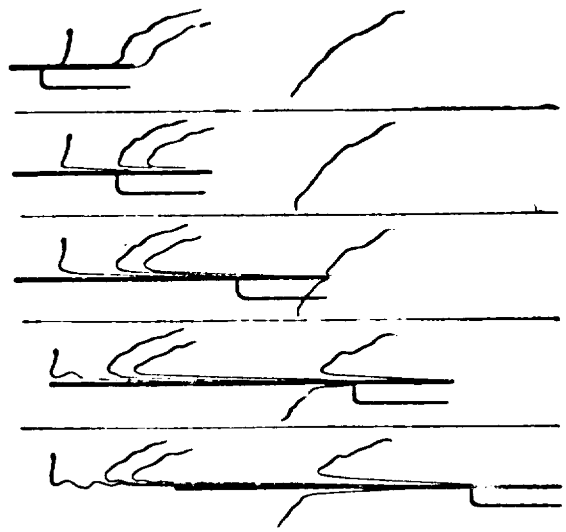

Fig. 5. Specimens of results with moving picture camera.

described method are given in Fig. 6. As is seen, for values of the abscissa greater than $\sqrt{x} = 0.6$ there is observed a considerable scatter of the test points, while for smaller values of $\sqrt{x}$ they lie well on a straight line.

The experiment therefore well confirms the theoretical considerations on the character of the flow in the boundary layer and on the relation between this character and the magnitude of the circulation about the wing.

Conclusions

Due to the unstable velocity profile near the leading edge the flow in this region has an unsteady character even in the case where in the remaining part it is quasistationary.

In the region adjacent to the leading edge, vortices are periodically formed moving toward the trailing edge with different velocities on the upper and lower surface of the wing.

Steady motion in the boundary layer sets in at a certain definite time after the start of motion of a given type, for example after a change of the angle of attack of the wing.

In the case of unsteady motion (for example in the case of an oscillating wing) a delay of the flow separation is for this reason possible with the consequence of an increase in the wing lift force.

Although the theoretical considerations and experimental data are given for the case of laminar boundary layer and incompressible fluid, it may be assumed that the obtained results can in principle be extended to the case of turbulent flow in the boundary layer and also to the case of a compressible gas.

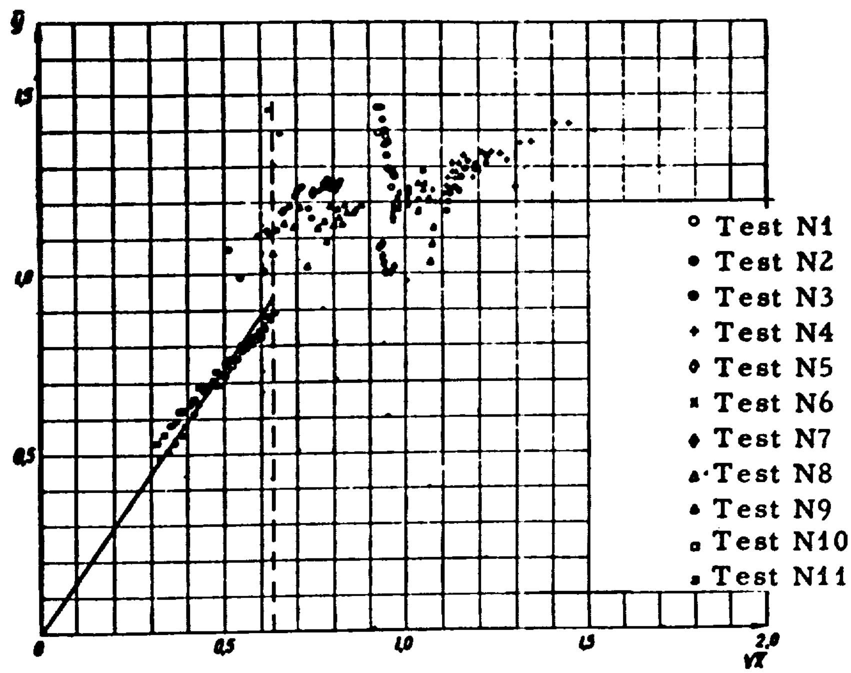

Fig. 6. Results of evaluation of experimental data.

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